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PHYSICS IN INDUSTRY

Physics in Relation to the Development of the Internal Combustion Engine

By

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Lecture No. 16

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PHYSICS IN RELATION TO THE DEVELOPMENT OF THE INTERNAL COMBUSTION ENGINE

IN the history of the development of prime movers or, in fact, of engineering machines generally, the path of development has rarely been more guided by the hand of physics than in the case of the internal combustion engine. Each important step forward has been undertaken only after an exploration by physical means.

In the investigation of the heat processes in the cylinder, of the units going to useful work, and of those lost in cooling and exhaust, of the effect of variable specific heat, dissociation, after-burning, and other factors, many ingenious experiments with original apparatus have been carried out.

In later times when maximum pressures mounted up, heat flow increased and the speed of revolution also, research work in the characteristics of the materials used became important. Exceptional accuracy in the engine parts themselves was then so necessary that special instruments of precision were called for to secure it.

As development went on, apart from the primary and secondary out-of-balance vibration of reciprocating masses, the high speed high pressure multi-cylinder engines developed dangerous torsional vibrations within the range of revolution speed, when useful research work again shewed the way to security. Similarly with each progressive step, difficulties arose, were elucidated, and the laws governing the new phase clearly set out.

At the present time a vast amount of research work is being carried out in connection with the injection and combustion problems of the quick running compression ignition engine. The true determination of the various factors affecting this problem has assumed such importance as to overshadow much of the work done before the War on mixture engines, which has now, perhaps, lost some of its earlier consequence.

The internal combustion engine in its earlier years may be considered just a mechanical contrivance and those engaged in its construction were more concerned in their own designs, with the immediate practical difficulties of burning a gas and air mixture within the cylinder and conveying the pressure produced from the heat evolved by means of a piston and linkage to the crankshaft as a usable power than to the physical processes upon which the economical action of the motor itself depended.

No doubt, during this mechanical age some theoretical consideration was given to the subject, experimenters examining their designs in the light of such information as they had of the physical characteristics known at the time.

We might, as an instance of knowledge or foresight, take the inventions of Barnett, in 1838. He invented three engines, each shewing marked novelty, but the outstanding feature was the introduction of the principle of compression, which has been the mainspring of economy ever since. The mechanical age continued some time after Barnett, and various linkage devices, such as the free piston engine, were tried, until design finally settled down to the conventional crank and connecting rod of the reciprocating prime movers that we have to-day. During this period but little scientific research was carried out and this is doubtless the reason for many erroneous ideas continuing to be held of the working processes of the engine. Such an idea was that of Lenior, who supposed that the economy of the engine would be improved by a slower rate of explosion or combustion.

The advantages of compression were again stated by Schmidt in 1861, and became more widely appreciated. The pamphlet of Beau de Rochas in 1862, which has formed the basis of most internal combustion engines, stated that there should be

1. The greatest possible cylinder volume with the least cooling surface.
2. Great rapidity of expansion.
3. The greatest possible expansion; and
4. The greatest pressure at the beginning of expansion.

These, he said, meant:

1. Suction during the outstroke of the piston.
2. Compression during the following instroke.
3. Ignition and expansion during the third stroke.
4. Discharging the burnt gases on the fourth stroke.

Here we have the famous four-stroke cycle, which was put into practical form by Otto in 1876, and is embodied in the majority of engines to-day.

The other well-known cycle, the two-stroke, was invented by Dugald Clerk in 1877. He was its most distinguished exponent, and was later to add much to our knowledge by his research work into the heat processes of the engine.

In the internal combustion engine using liquid fuel, a notable invention was that of Akroyd Stuart (1890) in which he employed a charge of air alone, and injected the spray of fuel into it within the cylinder during the compression stroke. In a later patent, he introduced a dividing wall into the combustion chamber with a connecting passage of small area. Both inventions have many derivations to-day. Two years later followed Diesel, the best known name to the general public in the internal combustion engine world.

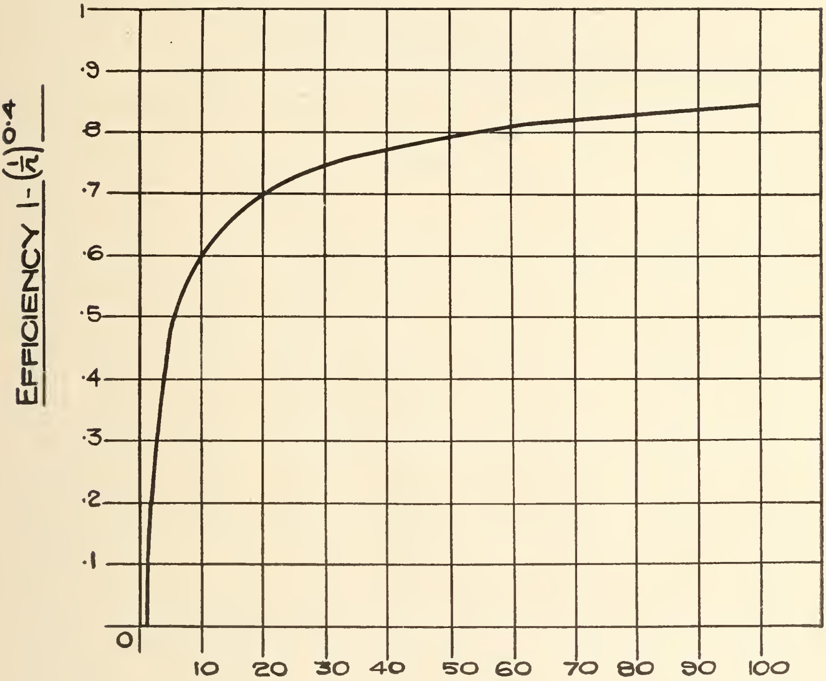


Fig. 1.

Compression Ratio π.

Theoretical Thermal Efficiencies for Different Compression Ratios in Three Symmetrical Cycles.

Physical research work on the engine in this country in the days before the War, is often synonymous with the name of Dugald Clerk, who did so much in investigating the heat processes of the engine himself, and in co-ordinating and classifying the work of others.

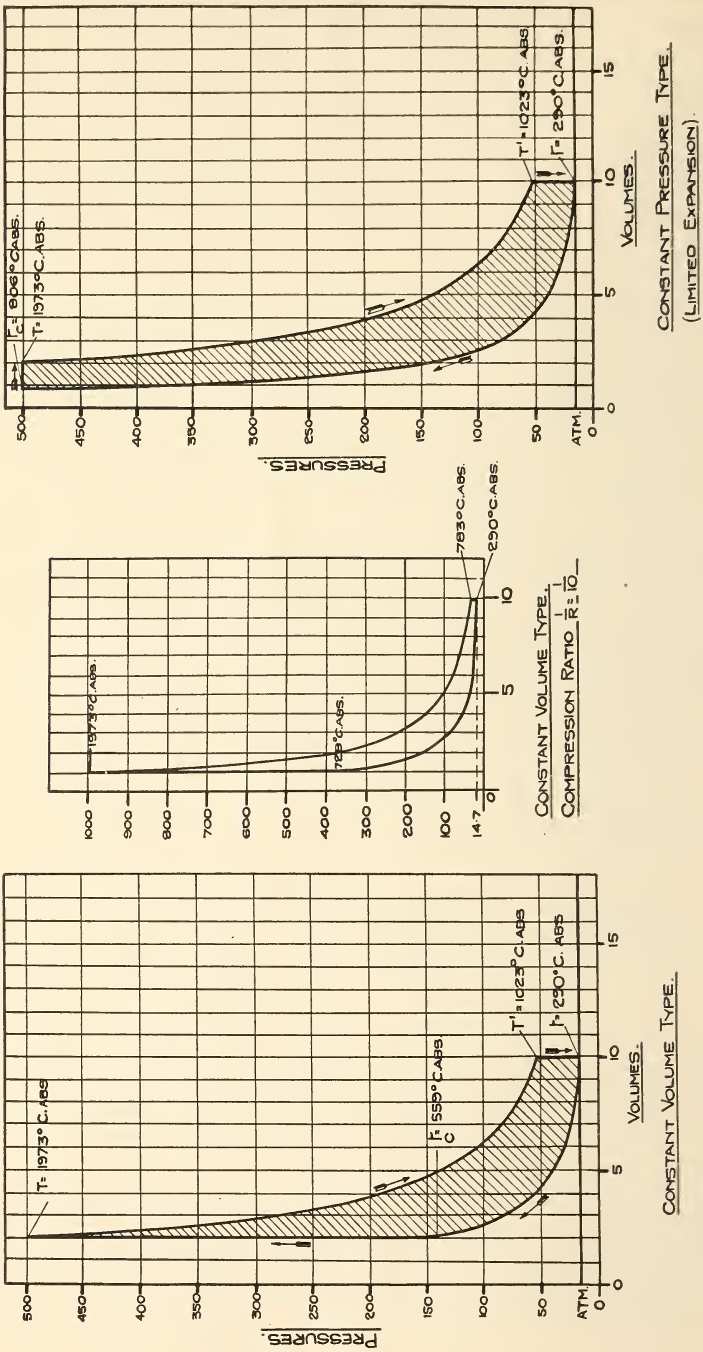

T_c = 806°C ABS.
T = 1973°C. ABS.
T' = 1023°C. ABS.
T = 290°C. ABS.
500
450
400
350
300
250
200
150
100
50
ATM.
0
PRESSURES.
0
5
10
15
VOLUMES.
CONSTANT PRESSURE TYPE.
(LIMITED EXPANSION).
1973°C. ABS.
723°C. ABS.
783°C. ABS.
290°C. ABS.
1000
900
800
700
600
500
400
300
200
100
14·7
0
5
10
CONSTANT VOLUME TYPE.
COMPRESSION RATIO $\frac{1}{R} = \frac{1}{10}$
T = 1973°C. ABS
T_c = 559°C. ABS.
T' = 1023°C. ABS
T = 290°C. ABS
500
450
400
350
300
250
200
150
100
50
ATM.
0
PRESSURES.
0
5
10
15
VOLUMES.
CONSTANT VOLUME TYPE.

Fig. 2.

He classified engines in three groups in 1882:

Type 1. Explosion acting on piston connected to crank. (No compression.)

Type 2. Compression, with increase of volume after ignition, but at constant pressure.

Type 3. Compression, with increase in pressure after ignition, but at constant volume.

Only those cycles employing compression have remained in use, and the development of the engine can be readily expressed in the steady rise in the ratios used.

The theoretical efficiency curve for different ratios of compression of three symmetrical cycles is given in Fig. 1.

Types 2 and 3 are those found in use to-day and they are given with their variation from symmetry in Fig. 2.

A diagram is added of a constant volume cycle with a 10 : 1 ratio.

This indication of the present day possibilities of the mixture engine, with doped fuel, shews the high ratio such a type of engine with suitable liquid fuel has now reached. On the other hand, with waste gas such as is obtained from blast furnaces, a similar ratio is attained.

This diagram may also be taken as a theoretical example of the low ratio injection engine, in which extra heat over that due to the compression is required, and also for the ignition of the fuel at starting.

In actual practice in the injection oil engines of to-day, heat is always added to the cycle at constant pressure as well as constant volume—the so-called dual cycle, and for purposes of safe ignition the compression ratio is generally higher.

There are other cycles that have been used, notably the Atkinson or extended expansion, and the search for higher economies will bring these up again for reconsideration in the near future.

A diagram from this type of engine is given in Fig. 3.

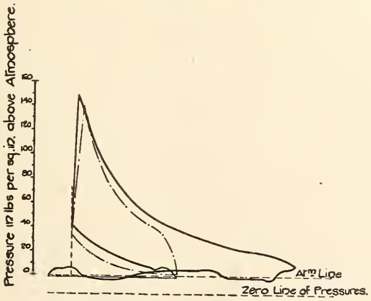


Fig. 3.
Diagram from Atkinson Cycle Engine.

The Humphrey Pump is perhaps the only example of this type at work to-day.

By reason of the limitations set up by the water surface upon which the explosion takes place, the compression ratio used is low, and yet the gain from the extended expansion is considerable. See Fig. 4.

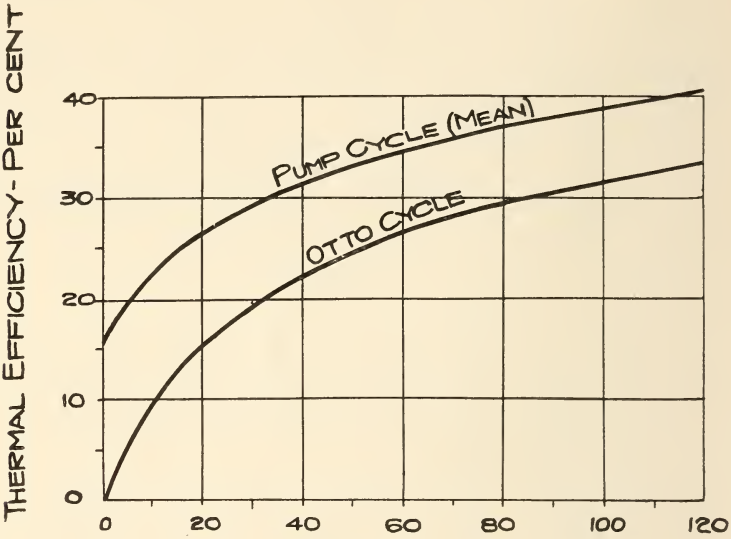


Fig. 4.

Practical Efficiency Curves 0·71 of Air Standard.
Compression Pressure in lb. per sq. in. above Atmosphere (Humphrey).

With the foregoing in mind, a suggested diagram from an extended expansion engine, but working with injected fuel at a suitable compression ratio (self-ignition) and heat added at constant volume and constant pressure, is given in Fig. 5.

Returning to the general consideration of the efficiency curve given in Fig. 1, the efficiency at first improves rapidly with rise of compression ratio, gradually falling as the ratio is increased; hence, we find that 15 : 1 is rarely exceeded.

Few, if any, engines have actually been built with such a high ratio as 20, yet progress in materials and in mechanical accuracy may allow development to proceed again in this direction.

The original compression engines worked at constant volume, except the Brayton. As ratios were low, the increased economy from raising them was very considerable.

Naturally the advantages to be gained by increased compression, as they became known, spread rapidly and were reflected in design, so that the progress in the development of the engine that followed was almost entirely based upon the progressive raising of the compression pressure, each advance, however, entailing some modification arising from the experience gained with the previous step.

The effect of the increased heat flow on the shape of the combustion chamber, with that of the turbulence before and after ignition, was not at that time understood.

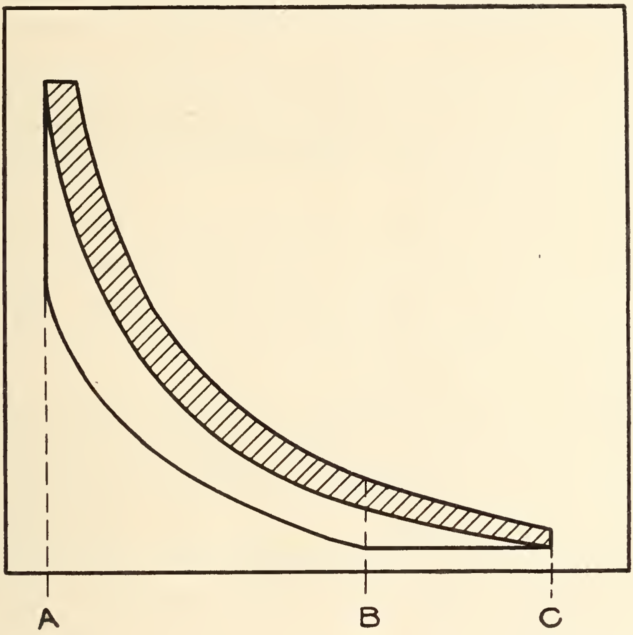


Fig. 5.

Suggested Modern Form of Diagram for Oil Engines with Extended Expansion: Heat Supplied partly at Constant Volume and Partly (Hatched) at Constant Pressure.

Normal A to B; Extra B to C.

The maximum pressures resulting from the increasing ratios of compression, apart from the design of the combustion chamber, affected the weight of the engine, then the formation of it, that is to say, the shape of the bedplate carrying the stresses and also the quality of the material. Hence, progress was relatively slow. On the other hand, apart from economy, the development of the engine took place in size, larger and larger engines were built, and with these occurred difficulties of another nature, which had to be overcome. They arose in the main from the heat stresses, due to temperature drop through the increased thickness of the walls from the heat generated in the combustion space passing to the cooling water. These practical difficulties involved lengthy experimental work in devising new shapes and improved material to meet the conditions called for in the large engine.

An exaggerated form of heat stress is the uncooled piston, the centre of which is so much hotter than the circumference, imposing a limit on diameter which in certain experiments was determined by Hopkinson to be 21 inches for cast iron, although the use of aluminium has extended this.

The research work carried on was mainly with the constant volume engine using a gas and air mixture, on the useful and lost heat in the engine, the explanation of why the maximum pressure recorded was less than the calculated one, etc., and on the imperfections of the cycle.

For the failure to agree with the calculated curve, the discrepancy being marked, the chief explanatory reasons advanced were: Dissociation, Cooling from Wall Action, After-burning and Variable Specific Heat—all of importance in varying degree, but the latter the most.

Experiments first in the laboratory were eventually extended to lengthy ones with actual engines, under practically working conditions. By these experiments, carried out by the Institution of Civil Engineers, the various losses of the engine and the imperfections of its cycle were accurately determined. Such results from actual engines enabled those concerned with the manufacture to appreciate in which direction their progress must be guided.

These engines had cylinder diameters of 5·5″, 9″ and 14″, and the powers were respectively 6, 24, and 60 B.H.P. The results of these tests were of great practical value, and considerably helped the development of the engine; hence, one may give some of the figures.

In mechanical efficiency, the recorded figures obtained were: 0·835, 0·848, 0·864.

The indicator used was of the standard piston type, and this lack of agreement drew attention to the risk of incorrect readings from instruments of this nature subject to inertia, for the figures were corrected to: 0·84, 0·85, and 0·86.

This handicap of the then standard instrument led to the design of much improved types as the Hopkinson short stroke piston, diaphragm, optical, etc., and later to other types like the R.A.E. (Farnborough) used for high speed high pressure work.

The brake thermal efficiencies determined were: 26·1, 28, 29·9; and the indicated ones: 31, 32·9, 34·8. From these the figure used for relative efficiency is often taken at 0·7, though a higher figure is now sometimes used. The actual heat flow during explosion and expansion amounted to 16·1% and at the end of expansion to 49·3%.

Later, Hopkinson carried out a number of experiments on a Crossley engine at Cambridge, with an 11½ in.×21 in. cylinder.

He determined the mechanical loss at nearly full load and 180 revolutions per minute, divided up as follows:

Indicated H.P.—41 : Brake H.P.—36 : Mech. Eff. 87·8%

Suction (pumping loss) ..	1·4 H.P.=3·4%	I.H.P.
Piston friction	2·5 H.P.=6·1 ,,	,,
Other friction valve lifting ..	1·1 H.P.=2·7 ,,	,,
Total mechanical loss	5 H.P.=12·2 ,,	,,

Experimental work still continued, and in that done by Burstall for the Gas Engine Research Committee of the Institution of Mechanical Engineers in 1897, the town gas used previously was replaced by gas drawn from a Mond producer. One of the main objects of the test was to work with higher degrees of compression to ascertain how the results would compare with the calculated curve.

Tests with compression ratios of from $\frac{1}{4\cdot36}$ to $\frac{1}{8\cdot07}$, the latter giving a pressure of 200 lbs. per square inch, were carried out.

In these experiments a good deal of practical knowledge with relation to the engine, particularly at the higher pressures, was arrived at, more perhaps from the limiting side than any other. That is, the relative lowering of the efficiency working under such compressions for the test results indicated that the curve bent over, contrary to what had been expected, shewing that improvements in design and construction were clearly called for; a lower mechanical efficiency was evidently the explanation, for later experience with improved engines confirmed the calculated curve of increased compression ratios.

The reports of the Gaseous Explosions Committee of the British Association are a mine of information gleaned since 1908 by many careful researches of leading physicists, and they cover variable specific heat determined by Clerk's ingenious experiment

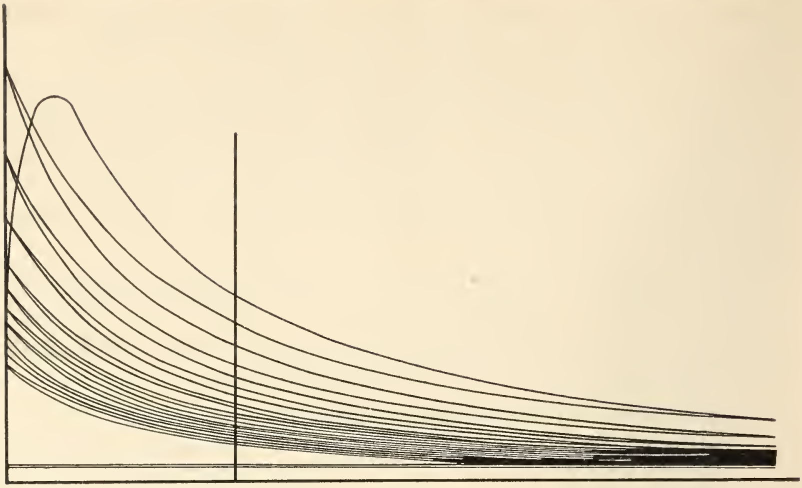


Fig. 6.

Clerk Diagram for Determination of Apparent Specific Heat.

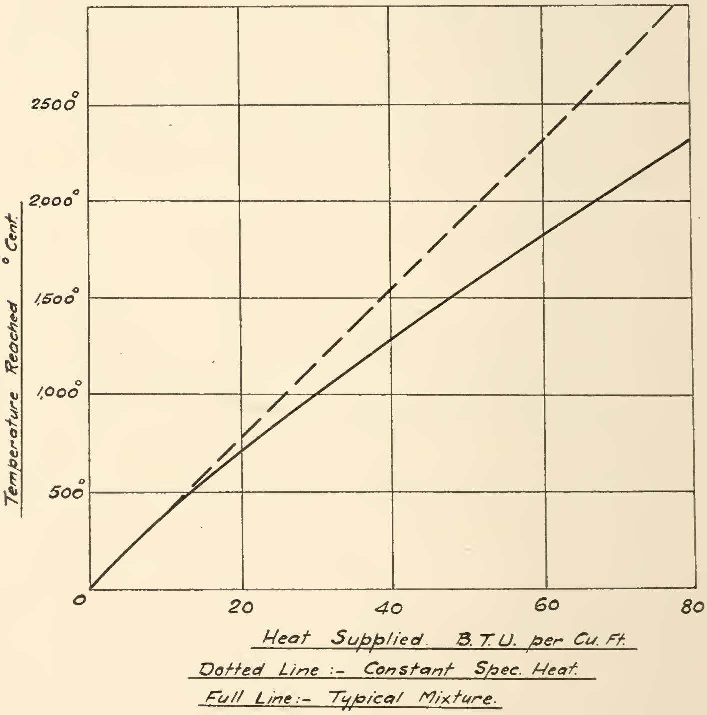


Fig. 7.

(see diagram, Fig. 6) and its effect, illustrated in Fig. 7, dissociation, radiation and turbulence, etc. David determined the loss by radiation to be as much as 26%.

In ascertaining the effect of turbulence, Clerk used an ordinary engine in the same way that he did in his zigzag experiment on specific heat, first drawing in the mixture and thereafter shutting the inlet valve, when after compressing and expanding the charge for one or two revolutions, he fired the charge. The diagrams taken indicate the very much slower rate of combustion as the turbulence died down (Fig. 8).

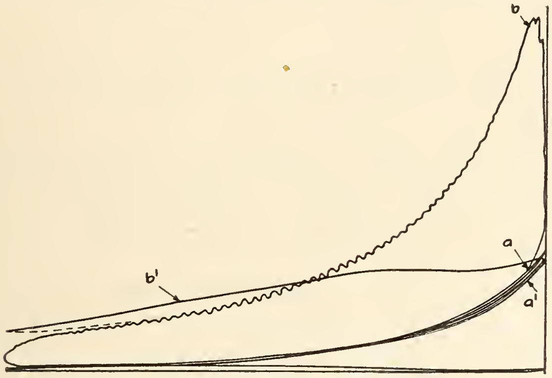


Diagram shewing Effect of Turbulence.
Ignition at Back of Combustion Chamber.
Time of Ordinary Ignition a—b, 0·037 second.
Time of Ignition without Turbulence a^1—b^1, 0·092 second.

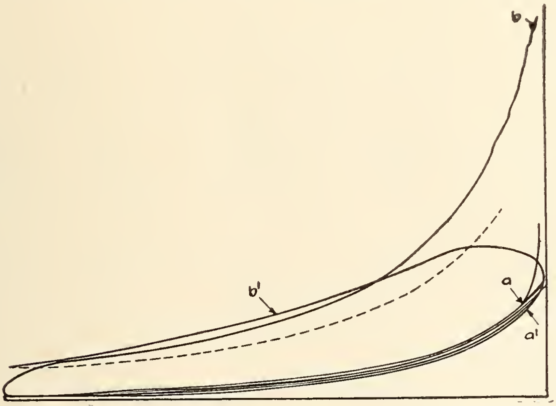


Diagram shewing Effect of Turbulence.
Ignition at Side of Combustion Chamber.
Time of Ordinary Ignition a—b, 0·033 second.
Time of Ignition without Turbulence a^1—b^1, 0·078 second.

Fig. 8.

Hopkinson carried out experiments on turbulence in a cylindrical vessel 1 ft. in diameter by 1 ft. long, a small fan being mounted in the centre to create the necessary turbulence. For the mixture of 10% coal gas and 90% of air, the time for ignition to maximum pressure with the gas at rest was about 0·13 seconds, with a fan running at 2,000 revolutions, 0·043 seconds, and 4,500 revolutions, 0·02 seconds.

The heat flow was double when the fan was running at the speed of 4,500 revolutions, that is, engines of high turbulence have a lower economy.

Hopkinson also examined the efficiency of scavenging in two-cycle engines by using a liquid of higher kinematic viscosity. He does not, however, appear to have applied this method to turbulence.

A good deal of attention was given at one time to stratified charging as a means of securing high economies, and the method may be returned to in future design. The results of a test in which the economy is marked are given in the table.

STRATIFIED CHARGING

RESULTS OF EXPERIMENTS MADE ON A LARGE GAS ENGINE

BY ALAN E. L. CHORLTON

Two-Stroke Cycle Light Load Slow Speeds

Date.	Average B.T.U.'s per I.H.P. Hour.	Indicated Horse Power.	Mean Effective Pressure.	Revs. Per Minute.	Indicated Thermal Efficiency.
3/7/13	5620	83·5	30·4	87·0	45·2%
3/7/13	5800	83·2	31·4	87·0	43·8%
3/7/13	6020	81·7	29·9	87·0	42·2%
3/7/13	5930	87·0	31·0	89·0	42·8%
Average	5843	83·8	30·7	87·5	43·5%

Approximate Contents of Working Cylinder:—
Volume of Cylinder = 8·49 cubic feet.
Volume of Mixture = 3·44 cubic feet.
Volume of Exhaust Products = 5·05 cubic feet.

Then volumetric and mechanical efficiency formed the basis of many valuable experiments to determine their values in all classes of mixture engines, and these were carried out by various experimenters. Of these turbulence ultimately became rather a popular one.

Then followed an extraordinary development of engines of the mixture type as the power units for aircraft. This brought into being a body of highly trained men who, with the special apparatus then evolved, accelerated progress enormously in the development of this type of engine.

Such developments in power and speed opened out a range of problems and the need for active research to solve them. The factors of weight and fuel economy were important; the first meant the use of improved materials, the second the highest compression ratio possible. Detonation, an explosive rate of firing of the mixture, has led to much experimental work in combustion chamber shape, heat flow, pockets, valve position, igniter, etc., and also in the fuels themselves, in which good work has been done by Fenning. Special apparatus was invented to determine the detonating point of the fuel used, and thereafter it was found that by suitably blending with benzol and later with metallic dopes, compression ratios could be raised to as high as 10 : 1, and weights reduced to below 1 lb. per B.H.P., an example of which is the Aero engine used in the Schneider Cup.

In the co-ordinating and bringing up to date of the research work that had been carried on, another committee on heat engine trials was appointed by the Institution of Civil Engineers, and reported in 1927. An interesting introductory note was given by Wells, and a valuable comment, differing in some degree, was read as a paper by Sir Dugald Clerk in 1928.

Turbulence as a controlling factor still maintained its popularity, and notwithstanding perhaps some overstatement and contrary explanations of its effects, when the high speed engine with injecting oil as fuel came into favour, its importance in its action on the oil sprays became even more prominent.

Though turbulence was at first determined by Clerk on a mixture charge engine, it appeared much earlier and in a more extreme form, with air alone, in the oil engine. It is doubtful, however, if the intention to disturb the air charge so violently was premeditated, or, what exactly took place was fully appreciated by its inventor.

This was the second patent of Akroyd Stuart, in which the combustion chamber was divided into two by a partition, the two parts being connected by a relatively small orifice, resulting in the forcing of the air charge from one side to the other during the compression stroke, whereby a more violent turbulence is set up than that arising from the speed through the inlet valves in the engines experimented with by Clerk.

No recorded tests of such a nature were taken of engines built with such devices in the earlier years.

They are not mentioned by Professor Robinson, who at that time was concerned with some other tests of the Akroyd Stuart engine.

Akroyd Stuart's intention, it is thought, was only to stratify the charge in such a way as to prevent too early automatic ignition.

This device of his, in the various forms which have been derived from it, had more effect on oil engine design, particularly in the smaller sizes, than any other factor. To-day it is almost essential with relatively small cylinders when running at high speed, where the period of time allowed for combustion is so small that it is necessary to accelerate it by artificial means. In this sense, the device of Akroyd Stuart has been a very potent one. Fig. 9 shews his device, and many forms have arisen from it; that is to say, combustion chambers divided into two of varying relative capacities. Fig. 10 compares the two types.

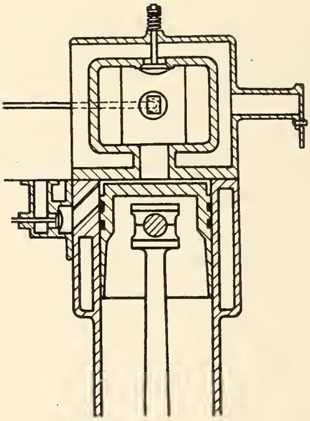


Fig. 9.
Section, Akroyd Stuart Divided Combustion Chamber (second patent).

The degree of turbulence in engines varies from below 200 ft. per second up to above 600 ft. per second. In the lower speeds the turbulence is in most cases set up by the inlet valve when the direction of flow is of such a disturbed nature that it may be classified as disorderly. In other cases, notably with two-cycle engines, when tangent inlet ports are employed, a rotary action is set up, the flow is more regular, and can be classified as orderly.

At present, the relation between the two is not quite clear, nor as to their exact movement of flow and reaction upon the oil jets. Normal turbulence is of the order of up to 300 ft. per second; above 400 ft. per second it is usually of the forced or disorderly type from an Akroyd Stuart neck or throat. More research work is required to compare and examine this important factor. If the effect of the degree of turbulence on the size of jet and on the rate of combustion can be put in graph form, it will be useful.

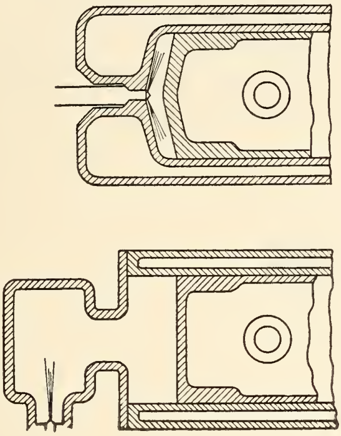


Fig. 10.
Combustion Chamber.
1. Cell.
2. Cell—hot bulb.
Pre-combustion.
Turbulent Pocket.

The Diesel oil engine occupies rather an isolated and singular position in many respects, in the history of internal combustion engine development by physical research, even when viewed in the whole range of prime movers, for it slipped at once into the leading position by its high heat efficiency after the preliminary mechanical difficulties had been overcome.

The high efficiency of the first engine is but little improved even to-day, and one can think of no other prime mover in which this has been the case.

Development has been largely mechanical, in improved accuracy and design of detail, and in very large sizes as used in marine work.

It is remarkable that but little research work with the true Diesel engine has been published. By the injection of the fuel by air it obtained adequate turbulence, with excellent combustion, and its high ratio of compression secured it at one bound a degree of economy much in advance of contemporary types.

Its isolation was such that but little effect was felt in the design of other oil engines in this country; it was a close school of its own. Steady progress, however, was made with the native born engines using airless injection, with gradually rising ratios of compression and less and less surface left uncooled to provide the ignition temperature.

A notable forward movement was the Vickers airless submarine engine manufactured by many firms during the War.

Thereafter followed a rapid development in the direction of speed of revolution, engines for the air and for the road calling for special features and light weights, considered as quite impossible by the school of Diesel design.

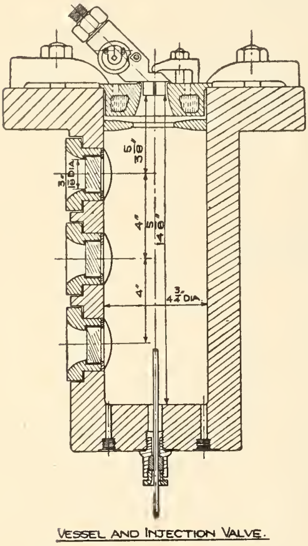


Fig. 11.

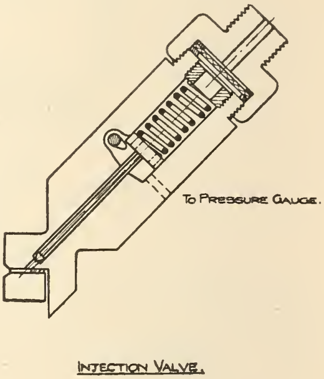


Fig. 12.

The advance of the airless type with the rise in speeds swung the pendulum to the other extreme, and an extraordinary amount of research work began.

This was first concerned with the behaviour of a jet of oil, representing an injection nozzle, when discharged through a small hole at high pressure. Many different experiments have been carried out determining this action.

Bird, in the Cambridge Engineering Laboratory, used a piece of apparatus shewn in Fig. 11, in which were three plate glass windows for observation of the flame at the start of combustion;

the hole used was square and the injection valve as in Fig. 12. He also used a kinematograph to assist in the examination of the flame. The actual impact of an oil jet tried in different ways was examined by Riehm and others.

In research on jets the National Advisory Committee for Aeronautics of the United States has contributed a most varied, extended and valuable analysis.

In the works test house, by means of an oscilloscope, the exact action of a jet leaving a nozzle can be observed, and the sharp shut off at the end without after-dribble, a necessity for economy and good combustion, is ensured. This hydraulic action depends on the relative perfection of the apparatus, that is, the supply pump and the cut-off valve.

The behaviour of the nozzle has been examined both with intermittent pump action and constant pressure systems with timing valves.

Many forms of nozzles of the open or closed types, with single and multiple holes (pepper box), flat annular, and with inward and outward opening valves, have also been tested.

An ingenious method has been devised by de Juhasz for measuring the velocity of the spray by a stroboscope apparatus of two revolving discs.

The research facilities at the Pennsylvania State College, where these tests were made, are organised to examine:

1. The physical properties, viscosity, specific gravity, elasticity and surface tension of the oil.
2. Nozzle, orifice area, shape and length.
3. Pressure of oil.
4. Pressure into which injection takes place.
5. Duration of spray.

In the special apparatus devised for the National Advisory Committee for Aeronautics in order to determine turbulence effects on combustion chamber form, types for high and low forced turbulence were used. If the turbulence is low, the spray must fit, so to speak, the combustion chamber to meet all the air possible.

In the forced turbulence type (Akroyd Stuart) on the American test, the speed of combustion was so increased that a rate of pressure rise of 1,080,000 lbs. per square inch per second has been obtained, which is stated to be three times greater than the optimum condition in a carburettor engine.

Bird continued his work on jets and oil flow through nozzles by examining the effect of turbulence, in which he used a rotating fan in the chamber coaxially with the jet but outside it. This type of turbulence is orderly rotating round the cylinder with the flow across the jet. Sass also made experiments on the air movement of this nature. (Fig. 13.)

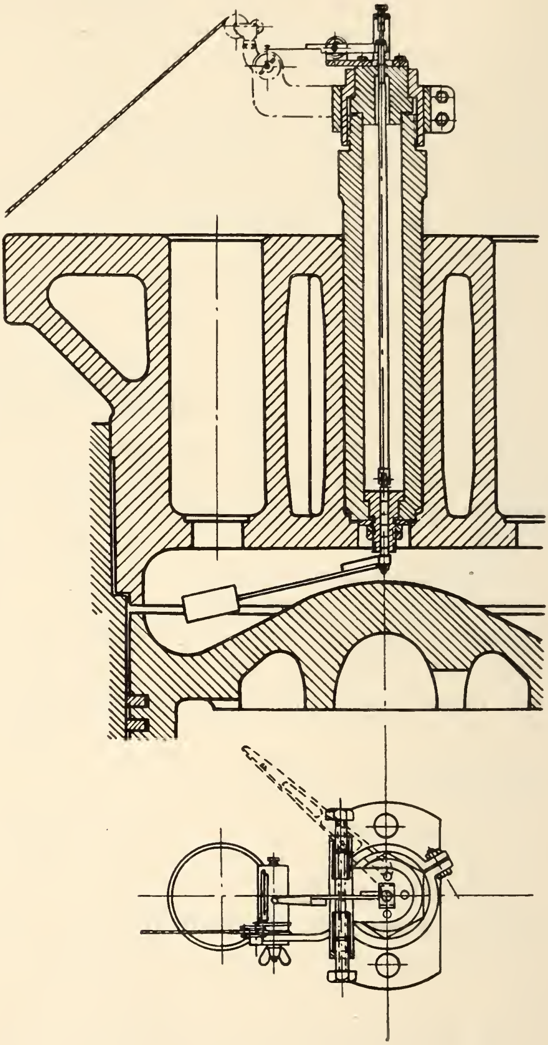


Fig. 13.
Apparatus to test rotary turbulence (Sass).

In the charging of two-cycle engines, the movement in the combustion chamber of forced turbulence in relation to the oil jet or jets is not yet clear, but the effect is so much greater at the higher air speed that a less efficient atomisation can be used, and the speeding up of combustion has led to increased use of this type on high speed motors requiring a clear exhaust.

In work done on the size of the oil globules when the jet is broken up it is suggested (Sass) that to obtain good combustion 30% of the oil globules in the jet should not exceed 0·0002 inches, 30% 0·0006 inches, and none should be larger than 0·002 inches.

In the length and capacity of the fuel main from the injection pump to the sprayer, the important factor is found to be the length, as might be expected, and secondary vibrational discharges are possible when the conduit exceeds a certain length and bears relation to engine speed.

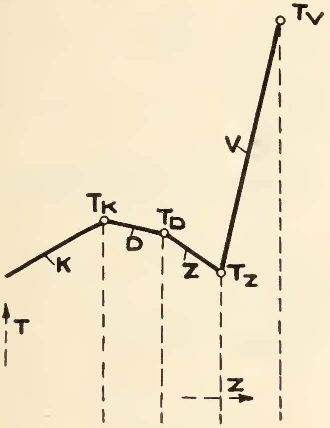


Fig. 14.
Gas Oil (Riedler 1916).
K = Compression.
D = Vapourisation.
Z = Decomposition.
V = Ignition and Combustion.

The lag period between the ending of compression and the beginning of ignition has occasioned much discussion. An earlier diagram (1916) is shewn in Fig. 14 as illustrating what probably takes place.

Though it will be gathered that a great amount of work has been done, there is still much to do in further ascertaining the action of forced turbulence on the jet, and in the determination of after-burning.

In high speed engines combustion goes on down the expansion stroke, lowering the efficiency so much that it may be in certain conditions the largest missing quantity in the cycle. This enquiry is being made by sampling valves tapped into the combustion chamber to operate at any pre-determined point.

In the examination of cylinder pressures at different points in the cycle, the special indicator devised by the Royal Aircraft Establishment has been very helpful, and a diagram, Fig. 15, taken from a cylinder similar to that of the engines of R.101, is interesting. The lag in ignition can be observed.

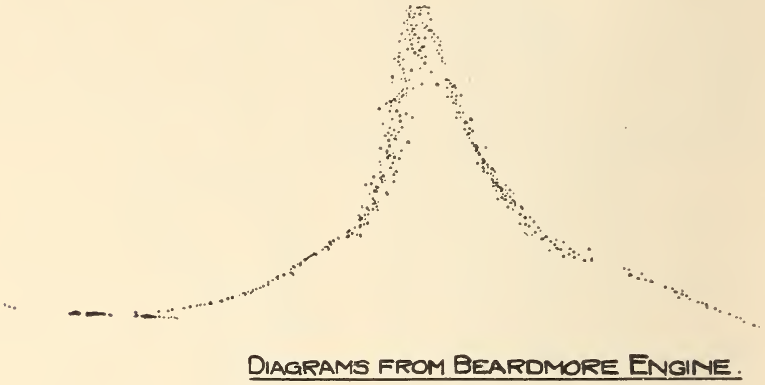
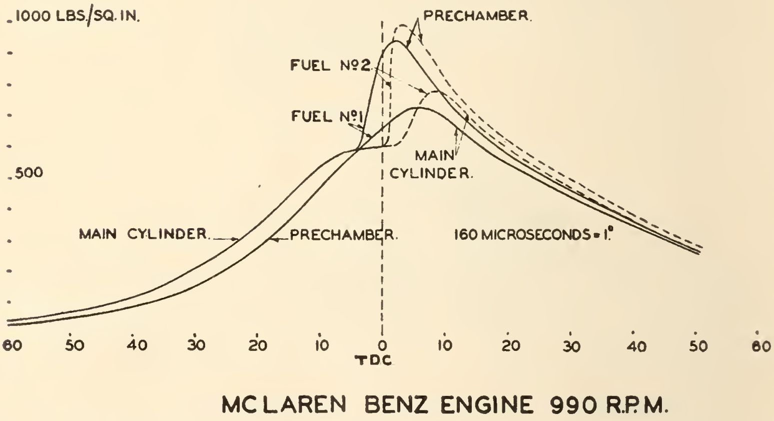


Fig. 15.



(Reproduced by courtesy of the Institution of Petroleum Technologists)

Fig. 16.

A combined diagram taken with an R.A.E. instrument on a pre-combustion chamber engine is shewn in Fig. 16 (LeMesurier).

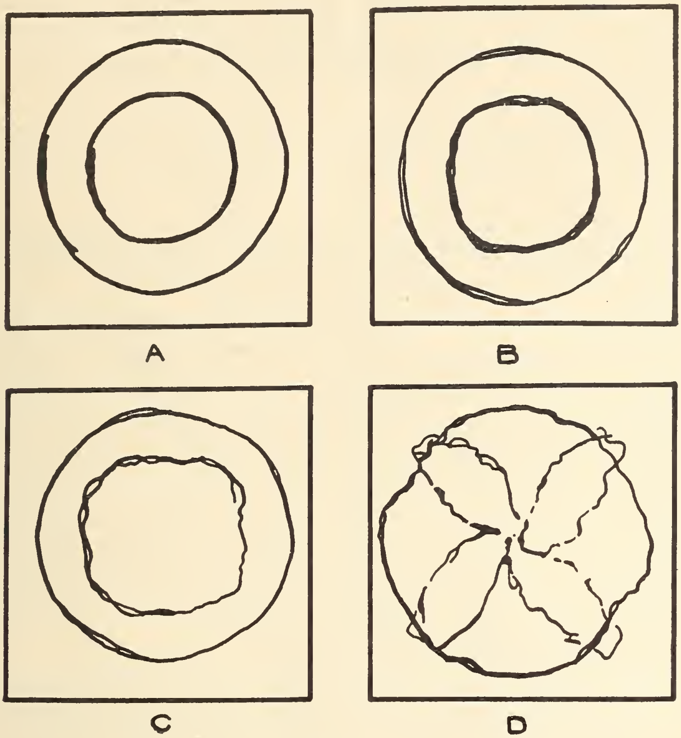


Fig. 17.

Torsiograph Records showing Crankshaft Vibrational Amplitudes.
R.101 Tornado Eight-Cylinder Diesel Engines.

A — 450 r.p.m.
B — 750 r.p.m.
C —850 r.p.m.
D —950 r.p.m.

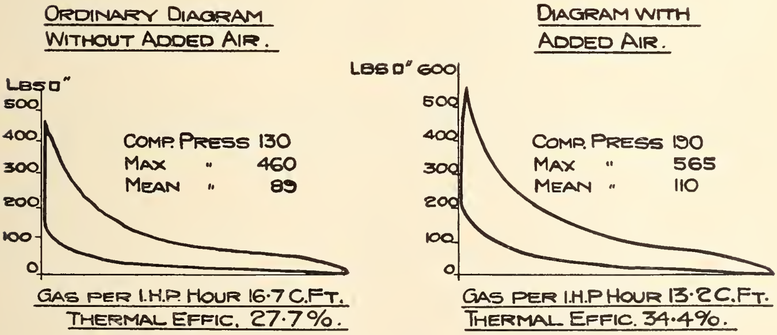


Fig. 18.

In the practical development of the high speed oil engine, many cylinders have become inevitable to obtain high powers, and with the high maximum cylinder pressures occurring, critical torsional vibrations of the crankshaft have often assumed very great importance.

Those of the engines for the R.101 are a notable case investigated by Carter. A, B, C, and D in Fig. 17 are taken by the apparatus he used.

It is not always possible to move the major critical outside the running range by stiffening up the shaft, so dampers have been devised to choke or absorb the amplitude effects.

Some brief reference to supercharging may be made, as it offers a field for development in the future, particularly with the oil injection engine. Originally it was devised by Clerk, not specifically to increase the mean pressure but more to reduce the maximum flame temperature by diluting the charge, the larger engines at that time suffering from cracks in the combustion chamber, pre-ignition, etc., due to heat conditions. What he did is illustrated in Fig. 18. Improvement of material has, however, limited the use of the added air so that to-day it is almost entirely a means of increasing the power output of the cylinders by the higher mean pressures made possible.

In small cylinders in this way some extraordinarily high figures have been obtained. In the Schneider Cup engine 200 lbs. per square inch B.M.E.P. was reached, and in experimental work over twice that figure. This development opens out an increased possibility for the compound engine.

In Clerk's engine of this type the transfer valve between the high and low pressure cylinder was a source of trouble and heat loss, but better results can now be more hopefully expected with improved material and the transfer valve of piston or liner form as these give better cooling without undue loss of heat, short passages and good effective area.

Fig. 19, by Yeates, illustrates the development of oil engines 1890 to 1930, considered from features of design.

In mechanical efficiency there is some gain due to the improvement of lubrication; otherwise, the figures are not much different from the original ones determined by Clerk and later when Hopkinson shewed piston friction to be 0·6 of the whole. This important feature requires more investigation. Stanton has found the lubrication to be of the boundary order. More research might improve the method of packing against the pressure.

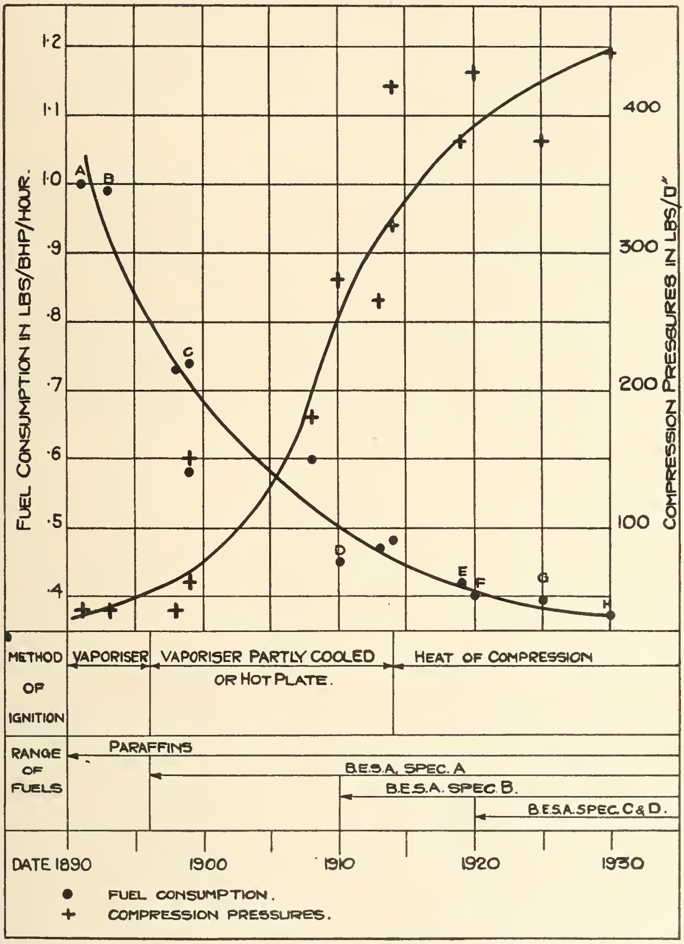


CHART ILLUSTRATING DEVELOPMENT OF OIL ENGINES FROM 1890-1930, SHOWING RISE IN COMPRESSION PRESSURES AND DECREASE IN FUEL CONSUMPTION (YEATES).

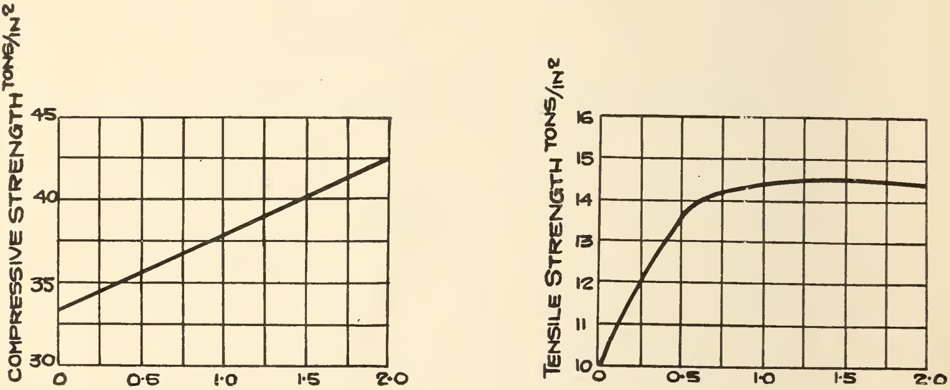
(*Reproduced by courtesy of the Diesel Engine Users' Association*)

Fig. 19.

In the early gas engines the material used for the working cylinder was always cast iron. As development went on and pressures rose, together with maximum temperatures, difficulties began to arise from cracking and it was obvious that the physical properties of the material must be modified in some way. At first design was changed to try to overcome such difficulties, and castings were made to have expansible connections between parts working under different temperatures.

When growth in the casting became a trouble due sometimes to too great a proportion of silicon, mixtures had to be changed to some degree and annealing processes explored before this was overcome.

As the engine grew larger, even cast iron, under the heat stress set up due to the thickness of the walls, proved insufficiently strong, and therefore, for all large engines, steel cylinders eventually became standard.



Per cent. Nickel.

Per cent. Nickel.

Fig. 20.

In smaller engines cast iron was still used, but of a special nature, like perlit, or later still through the addition of nickel, etc., castings were made entirely suitable to the much higher stress conditions of high compression engines. (Fig. 20.)

The table shews the reduction in expansion coefficient.

Percentage of Nickel.	Coefficient of Expansion per degree C.
26	0·00001312
28	0·00001131
28·7	0·00001041
30·4	0·00000458
31·4	0·00000340
34·6	0·00000137
35·7	0·00000087
37·3	0·00000356
39·4	0·00000537
44·4	0·00000856
47·5	0·00000870
Ordinary Mild Steel	0·00001078
Ordinary Hard Steel	0·00001240

There is little doubt that the progress in the development of the engine was at times held up almost entirely until a more suitable material could be found to meet the case.

In the very high speed engines of large output, metals of higher conductivity were inevitably called for, and those made use of are special aluminium alloys for pistons, cylinder covers, etc. In the forged state in particular, such materials give excellent results.

Some progress has taken place also in the use of magnesium alloys because of their low specific gravity, coupled with very good heat conductivity. Here again the forged conditions produce a much more lasting material than with castings.

For crankshafts, connecting rods, etc., special steels were developed with exceptionally high stress and impact values. An example is shewn in Fig. 21.

For exhaust valves to resist the great heat, high nickel chrome alloys have been successfully introduced, a strength of 34·5 tons being retained at 700°C.

The great need for the surface hardening of parts for quick running engines to resist wear has at last resulted in the invention of a system whereby, after treating special steel with ammonia gas, an extraordinary hardness is obtained. Brinell hardness figures range from 900 to 1,100, equivalent to Shore scleriscope of 102 to 113 (Fig. 22). This looks to be of real benefit for the wearing

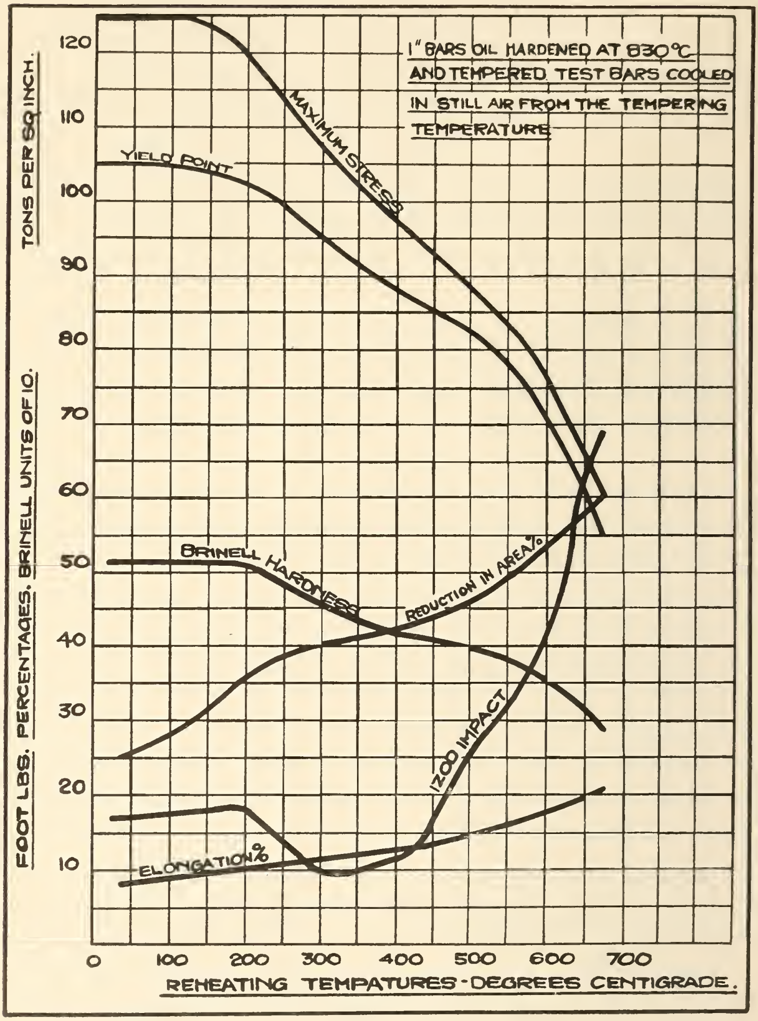


Fig. 21.
Shewing the Mechanical Properties of Vibrac, Molybdenum Steel V.45.

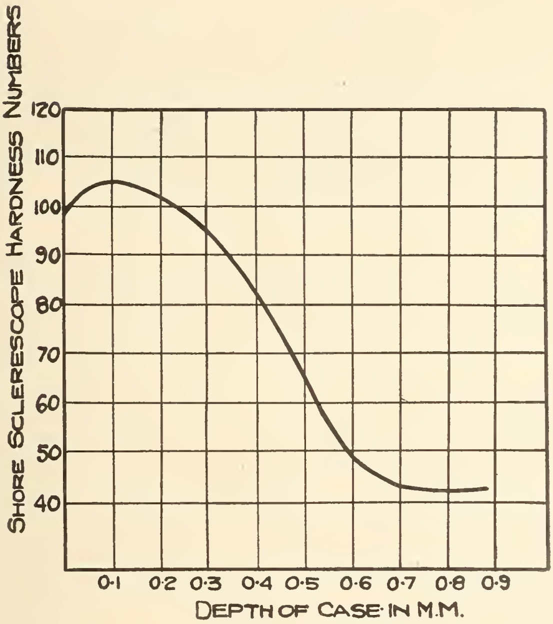


Fig. 22.

Curve shewing hardness of Nitralloy Steel, oil treated and reheated to give 64 tons tensile. Nitrated for 90 hours.

parts of the high speed engine, for the method is adopted for the cylinder liners also; in one case after 30,000 miles no wear was recorded.

There is no doubt that the real limitation to the use of high speed machinery depends primarily upon the resistance to vibration and repeated loading of the material used, but still more on its resistance to wear.

The advent of the aero engine tightened up all the measurements taken to make sure material was to specification, etc., as the factors of safety could only be limited as compared with the old lower pressure land engines. Inspection became more and more intensive to ensure reliability and freedom from breakdown in the air, and the following table from the Bristol Jupiter check of material illustrates the position admirably:

"BRISTOL" JUPITER AERO ENGINE

CHECKS ON ACCURACY OF PRODUCTION

Master Rod.	Limits.
Rod Centres	±0·003″
Relative parallelism of bores	0·0005″ per inch.
Big end, inside diameter	+0·0005″
Ovality and taper in big end bore to be within	0·0002″
Small end, inside diameter	+0·0005″
Wrist pin centres	±0·003″
Wrist pin bores	+0·0002″
Relative parallelism of wrist pin bores	0·0005″ per inch.
Twist permitted between main bore and wrist pin	0·001″ per inch.
Twist permitted between big end and small end	0·001″ per inch.
Side float on crank pin	0·007″
Crankshaft.	
Crankpin, diameter	−0·0005″
Crankpin ovality and taper to be within	0·0002″
Shaft, diameter for main bearings and cam gear	−0·0005″
Crank throw	+0·005″
Alignment of crank pin with main journals	0·0005″ per length of crank pin.
Alignment of main shaft	0·0005″ per length of shaft.
Ovality of journal bearings to be within	0·0003″

“BRISTOL” JUPITER AERO ENGINE PRODUCTION

CHECKS ON MATERIAL

1 Physical Tests.

Component.	Material.	Material Specification.	Rough Form.	Tensile Test.	Fracture Test.	Impact Test.	Hardness Test.	Etched.	Optical Test.	Hydraulic Test.
Crankshaft Front.	N.C.S.	3.S.11.	Stamping.	Buckton m/c. Yes.	No.	Izod.	Brinell.	No.		
Rear.						Avery.				
Master Conn. Rod.	N.C.S.	S.65.	Stamping.	Yes.	Yes.	Izod.	Brinell.	Yes.	Hand lens.	
Conn. Rod. Sleeve.	C.H.N.S.	3.S.15.	Stamping.	Yes.	No.	Izod.	Rockwell.	Yes.	Hand lens.	
Floating Bush.	C.P.B. & W.M.	B.8. & D.T.D. 15.	Cast.	Per Batch.	Yes.	No.	Firth’s Hardometer.	No.		
Articulated Rod.	N.C.S.	S.65.	Stamping.	Yes.	Yes.	Izod.	Brinell.	Yes.	Hand lens.	
Wrist Pin.	N.C.S.	2.S.28.	Bar.	Yes.	Yes.	Izod.	Rockwell.	Yes.	Hand lens.	
Gudgeon Pin.	A.H.S.	2.S.28.	Bar.	Yes.	Yes.	Izod.	Rockwell.	Yes.	Hand lens.	
Wrist Pin Bush.	C.P.B.	B.8.	Chill Cast.	Per Batch.	Yes.	No.	Firth’s Hardometer.	No.		
Small End Bush.	C.P.B.	B.8.	Chill Cast.	Per Batch.	Yes.	No.	Firth’s Hardometer.	No.		
Piston.	‘Y’ Alloy.	3.L.11.	Cast.	Per Batch.	No.	No.	Brinell.	Yes.	Hand lens.	Yes.
Cylinder Barrel.	Carbon Steel.	2.S.6.	Forging.	Yes.	Yes.	Izod.	Brinell.	No.		
Cylinder Head.	‘Y’ Alloy	DTD.58.	Stamping.	Yes.	No.	No.	Brinell.	No.		Yes.
Crankcase.	Dural.	DTD.18A.	Stamping.	Yes.	No.	No.	Brinell.	No.		Yes.

In high speed machinery successful operation depends primarily upon the parts being constructed accurately to fine limits in all respects. Without this, even if the material is of the requisite high class standard, failure will result if the accuracy is not extraordinarily high, particularly in such parts as crankshafts, connecting rods and pistons. This fine degree is well illustrated by the foregoing table of Bristol Jupiter practice.

It is rather to be regretted that more is not made of this fundamental factor of the successful engine. A department of mechanical imperfections of manufacture at the National Physical Laboratory would not be at all out of place, and by the dissemination of the knowledge obtained would, in the end, greatly increase the accuracy of mechanical products generally.

A new range of instruments is coming into use to ensure this required degree of accuracy, and some of the optical ones by Zeiss are very interesting.

By such accuracy we are enabled to carry successfully very heavy loadings in bearings at high speeds, as for instance, two tons per square inch on the piston pin and one ton on the crank-pin, while with the floating bush type P.V. figures up to 100,000 have been reached, quite twice those without it.

The lubricating medium must, of course, always be suitable and properly allied.

There is one form of internal combustion motor not mentioned in this lecture and that is the one using solid fuel, coal dust.

Some work goes on in Germany, a standard vertical type engine is running, and in another case work continues with a turbine using coal dust fuel.

This age is one of oil fuel, yet this country is essentially a coal country; its industrial supremacy was built up on coal, and some research work seems called for in the use of coal in prime movers.

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